DETECTION OF COHERENT STRUCTURES IN HIGH-FREQUENT TIME SERIES OF A MONOSTATIC SODAR-RASS SYSTEM

C. Thomas[1], J.-C. Mayer[1], F.X. Meixner[2], Th. Foken[1]

[1] Department of Micrometeorology, University of Bayreuth, Bayreuth, Germany
(christoph.thomas@uni-bayreuth.de)
[2] Department of Biogeochemistry, Max Planck Institute of Chemistry, Mainz, Germany

Abstract

This study aims to demonstrate the applicability of acoustic remote sensing to observing coherent structures above tall vegetated canopies and thus to get deeper insight into the dynamics of coherent structures. Therefore a Sodar-Rass system was operated during two field campaigns obtaining time series with a resolution of 0.4 Hz. Coherent structures were successfully observed in the vertical wind speed data. Comparisons with simultaneously operated sonic anemometers yielded a remarkable agreement in the wavelet variance spectra. The characteristic event durations of coherent structures were found to range from approx. 20 s to several minutes with smaller structures missing with increasing height. Coherent structures were found to exist mainly in the roughness sublayer above tall vegetation. Both small-scale and large-scale events were found to exist at the same time and possibly interacting with each other.

Keywords: coherent structures, ramps, tall vegetation, wavelet transform

1. Introduction

Coherent structures are an inherent part of the turbulent atmospheric flow over tall vegetated surfaces. They manifest themselves as low-frequent, non-regularly spaced ramp-like patterns in both vector and scalar time series and have been observed in the roughness sublayer in and above heterogeneous canopies by many authors (e.g. Bergström and Högström 1989; Gao et al. 1989; Paw U et al. 1992). The necessity of studying coherent structures becomes evident, as their origin and dynamical characteristics still remain poorly understood, their contribution to atmospheric fluxes can be significant (e.g. Collineau and Brunet 1993b) and their presence violates the assumption of stationarity for flux determination methods such as the eddy-covariance technique making it temporarily invalid.

Most studies that deal with coherent structures use time series obtained by sonic anemometers installed at towers. These data provide a high temporal resolution of commonly not less than 10 Hz, but they are limited in their maximum observation height and vertical resolution given by the instrumentation levels. Acoustic remote sensing can extend the vertical range of measurements, but is usually applied to obtain mean flow and scalars fields, with the drawback of a poor temporal resolution. This study attempts to fill this observational gap by obtaining time series with a sufficient time resolution for detecting coherent structures using a commercially available monostatic Sodar-Rass system. Coherent structures can thus be observed throughout the RSL and above. The main objective of this study is both to demonstrate the applicability and limitations of acoustic remote sensing for the analysis of coherent structures and to obtain results on their spatial and temporal characteristics. The latter are expected to allow deeper insight into their generation and dynamical characteristics.

2. Experimental setup and sites

The data used in this paper were obtained in two field campaigns, namely in the WALDATEM-2003 (WAveLet Detection and Atmospheric Turbulence Exchange Measurements) and in the ECHO 2003 (Emission and CHemical transformation of biogenic volatile Organic compounds) experiments, both conducted during summer 2003. The applied acoustic remote sensing system consisted of a phase array Doppler Sodar DSDPA.90-64 with a 1290- MHz- RASS extension by Metek Meteorologische Messtechnik GmbH.

2.1 Sounding parameters

The sounding parameters were selected to observe coherent structures in the vertical wind speed and temperature with a sufficient resolution in time. The antennas were limited to the vertical and radio magnetic antennas only. The acoustic sounding frequency was chosen as 2000 Hz. The resulting mean sampling frequency of the time series was determined to 0.4 Hz, i.e. single soundings could be performed every 2.5 s. The vertical range of measurements was from 35 m to 145 m and from 30 m to 140 m a. g. l. during the WALDATEM-2003 and ECHO 2003 experiments respectively. The height resolution was 10 m.

2.2 Experimental sites

The site of the complex exchange experiment WALDATEM-2003 is located in the Fichtelgebirge mountains, Germany at 780 m a. s. l. and covered by spruce forest with an average canopy height h_c of 19 m. The Sodar-Rass system was located in a small clearing (approx. 100 x 200 m) in a distance of approx. 200 m apart from the flux tower station GE1 of the CarboEurope Cluster, where continuous eddy covariance measurements are performed using sonic anemometers and fast response gas analysers.

The ECHO 2003 site was located at the Research Centre Jülich near Cologne, Germany at 45 m a. s. l. covered by mixed forest with a mean canopy height of 30 m. The Sodar-Rass was operated near the wastewater treatment plant in a large clearing (500 x 500 m) approx. 1000 m apart from the main meteorological tower. In addition to the Sodar-Rass data, turbulent time series were obtained using a sonic anemometer at the 120 m platform on the main meteorological tower.

3. Method of analysis

First, individual data of the recorded raw time series of the Sodar-Rass system were checked and selected for data quality using the error codes output of the system. The error code includes flags for important properties of the backscattered spectra and signal-to-noise ratios. Only data without any flag set were passed onto the further analysis. The next step was to fill the resulting gaps occurring in the time series by applying an interpolation algorithm (Akima 1970). Subsequently, the continuous time series were normalised with their mean and standard deviation.

The extraction and analysis of the coherent structures were performed using a software tool based on the wavelet transform. Only a brief description of the implemented procedures will be given. First, high-frequent fluctuations with small event durations were removed with a wavelet filter focusing on the low-frequent patterns only. The typical event duration of coherent structures in a time series was obtained from the wavelet variance spectra. The individual coherent structures were detected using the zero-crossing method of the wavelet coefficients (Collineau and Brunet 1993a) yielding their main temporal separation. The interested reader is referred to Thomas and Foken (2004) for a detailed description of the method.

4. Results

The time series of the non-dimensional fluctuations of the vertical wind speeds of all levels are shown for a period of 600 s during WALDATEM-2003 in Figure 1. The low-pass filtered data clearly show simultaneous upward and downward motions between neighboured levels, sometimes with a noticeable temporal shift. The fluctuations are found to be intensive in the interval 0 – 240 s, to be somehow suppressed from 240 – 360 s, while taking up again from 360 – 600 s. The lower levels, ranging from 35 m to 65 m, show consistent motions to a high degree, which suggest that they are due to the same events. The fluctuations in all time

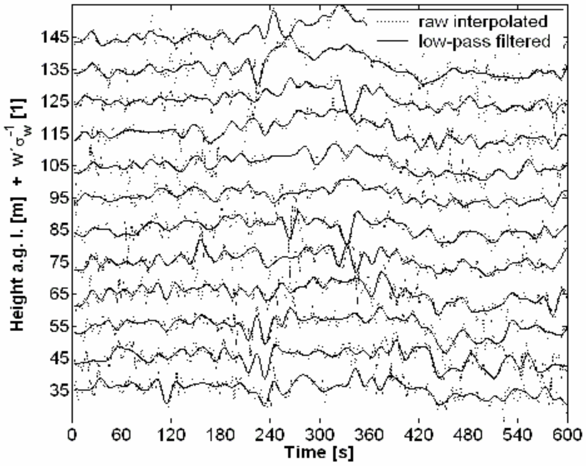

Figure 1: Time series of the normalised vertical wind speed of all observed levels at July 8th 2003 12:30 – 12:40 CET during WALDATEM-2003.

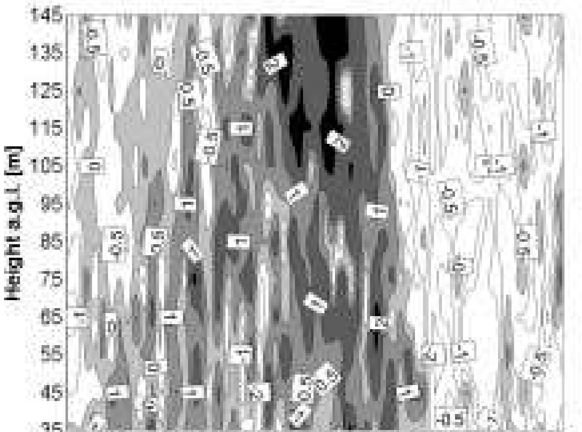

Figure 2: Corresponding contour plot of the low-pass filtered normalised fluctuations of Figure 1; updrafts are grey shaded, downdrafts are white.

series seem to exhibit events with various durations. The duration of the shortest and most apparent fluctuations can be estimated visually to approx. 20 s, being superimposed by longer structures. Figure 2 shows the denoised time series of the same period of time as a contour plot. Upward motions (gusts) are filled with grey shaded tones, whereas the colour intensity increases with increasing amplitude. Downwards motions (bursts) are generally represented as white-filled contours. Now the vertical structures, which span several levels, become even more evident. The most dominant structure covers the entire interval: A large-scale gust raising in height can be observed from 0 – 400 s reaching a height above the observation levels, followed by a rapid burst moving down from the uppermost to the lowest level in approx. 20 s and persisting beyond 600 s. This large-scale structure is continuously interrupted by small-scale motions predominantly occurring in the lower levels up to 65 m and showing a periodic change in sign. The observed both large-scale and small-scale events fulfil the definition of coherent structures given as a slowly developing upward motion followed by a fast downward motion quite well. However, the large-scale events might be due to convective processes as the atmospheric stability parameter zL^{-1} was determined to -0.53 during this period, where z is the measuring height and L the Obukhov-length. The friction velocity was determined to 0.57 ms^{-1}. Larger and smaller events seem to exist simultaneously, being well organised and most likely interacting with each other.

The normalised wavelet variance spectra of the vertical fluctuations for selected levels are displayed in Figure 3. The corresponding spectrum obtained by the sonic anemometer located at the flux tower approx. 200 m apart from the Sodar-Rass was included for reasons of comparison. The spectra of the 35 m and 45 m levels were combined, as a level of approx. 40 m corresponds best to the installation level of the sonic. The spectra for the 35 m + 45 m level and the sonic agree very well, exhibiting maxima at 18, 67 and 147 s event duration and 16, 51, 69 and 150 s event duration respectively. The 51 s maximum that was observed in the sonic data was lost in the Sodar data due to the combination of the lower two levels. The single spectrum for the 45 m level (not displayed here) was found to show a corresponding additional maximum at 46 s. The 55 m and 75 m levels show characteristic event durations at 17, 39, 62 and 144 s and 34, 45 and 172 s respectively. The detected maxima for the characteristic event durations support the observation that fluctuations in the lower levels up to 65 m are due to the same structures. This finding supports the hypothesis that coherent structures mainly exist in the roughness sublayer, which has an estimated height of $3h_c$. The good agreement with the sonic data point to the fact that both instruments observe the same coherent structures. This finding is strongly supported by the fact that the sonic was located downwind of the Sodar-Rass during the considered interval. The shortest characteristic events are missing at the 75 m level leading to the conclusion that large-scale fluctuations seem to dominate with increasing height.

Figure 4 shows an example for spectra derived from the Sodar-Rass and sonic vertical wind speed data during ECHO 2003: The 40 m level exhibits maxima at 47, 77 and 138 s, the 70 m level at 39, 72 and 142 s and

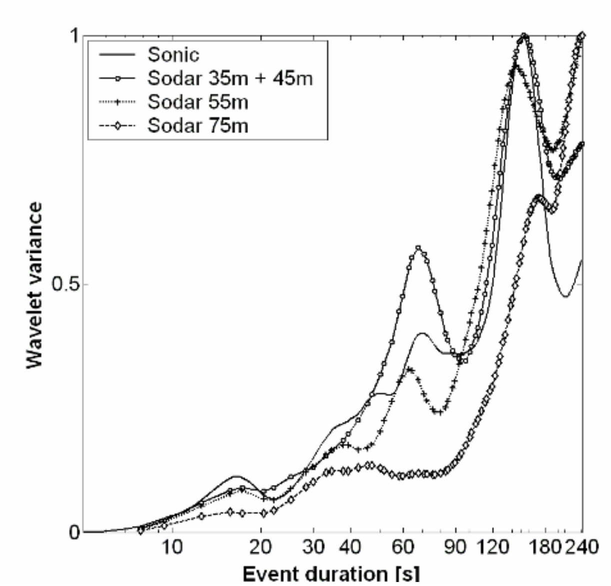

Figure 3: Normalised wavelet variance spectra of vertical wind fluctuations obtained by Sodar-Rass and sonic anemometer at July 8th 2003 12:30 – 12:55 CET during WALDATEM-2003.

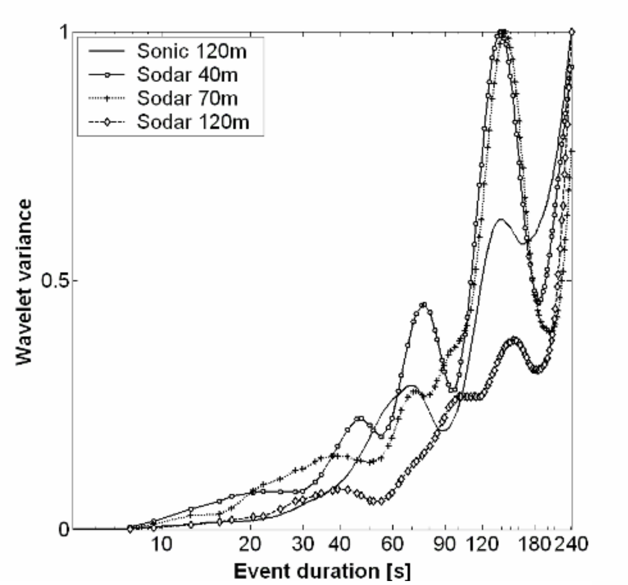

Figure 4: Normalised wavelet variance spectra of vertical wind fluctuations obtained by Sodar-Rass and sonic anemometer at July 29th 2003 15:45 – 16:10 CET during ECHO 2003.

the 120 m level at 39 and 153 s. The sonic, installed at the 120 m platform of the meteorological tower, shows maxima at 64 and 136 s event duration. Here, only the largest events agree quite well with the corresponding Sodar-Rass level, whereas the shorter events are closer to those detected in the lower 40 m and 70 m levels. This finding might be due to the fact that the tower is surrounded by 30 m high forest and the Sodar-Rass was located in a distance of approx. 1000 m in a large clearing, allowing the main flow to approach the surface. Thus, coherent structures that appear at the tower at a height of 120 m are expected to become apparent at lower levels in the clearing. The short coherent structures with approx. 20 s event duration, which were found in the WALDATEM-2003 spectra, cannot be found in the ECHO 2003 spectra. This finding points to different flow and surface conditions during the considered experiments.

The recorded and processed temperature time series of the Sodar-Rass system were not found to show any distinct fluctuation patterns but noise only. This result might be due to the selected small vertical resolution of 10 m. The manufacturer of the applied Rass extension recommends a minimum resolution of 20 m.

5. Conclusions

This study intended both to demonstrate the applicability of acoustic remote sensing for observing coherent structures in and beyond the roughness sublayer above tall vegetation and thus to get deeper insight into the dynamical characteristics of coherent structures. From the results the following conclusions can be drawn:

- The applied monostatic Sodar-Rass system was successfully found to be applicable to observing coherent structures in the time series of the vertical wind in the lower part of the atmospheric boundary layer above tall vegetation.
- The detection of coherent structures in the temperature traces failed most likely due to technical limitations of the applied Rass extension.
- Spectra derived from both tower-based measurements by sonic anemometers and data obtained by Sodar-Rass show great agreement at least for lower levels above the vegetation.
- The smallest coherent structures were found to have mean event durations of approx. 20 s, while the largest persist several minutes.
- Coherent structures were found to be present mainly in the roughness sublayer above tall vegetation with an estimated height of $3h_c$.
- Coherent structures consist of both small-scale and large-scale events existing simultaneously and are well organised.

Acknowledgments

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References

Akima, H., 1970. A new method of interpolation and smooth curve fitting based on local procedures. J. Assc. Comp. Mach., 17: 589-602.

Bergström, H. and Högström, U., 1989. Turbulent exchange above a pine forest. II. Organized structures. Boundary-Layer Meteorol., 49: 231-263.

Collineau, S. and Brunet, Y., 1993a. Detection of turbulent coherent motions in a forest canopy. Part I: Wavelet analysis. Boundary-Layer Meteorol., 65: 357-379.

Collineau, S. and Brunet, Y., 1993b. Detection of turbulent coherent motions in a forest canopy. Part II: Time-scales and conditional averages. Boundary-Layer Meteorol., 66: 49-73.

Gao, W., Shaw, R.H. and Paw U, K.T., 1989. Observation of organized structure in turbulent flow within and above a forest canopy. Boundary-Layer Meteorol., 47: 349-377.

Paw U, K.T. et al., 1992. Evidence of Turbulent Coherent Structures in and above Agricultural Plant Canopies. Agric.For.Meteorol., 61: 55-68.

Thomas, C. and Foken, T., 2004. Detection of Long-term Coherent Exchange over Spruce Forest Using Wavelet Analysis. Theor. & Appl. Climatol.: (accepted).